# Formation Flying for Assembly of Deep Space Interferometers

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## Collaborators

- **Ball Aerospace and Technologies**
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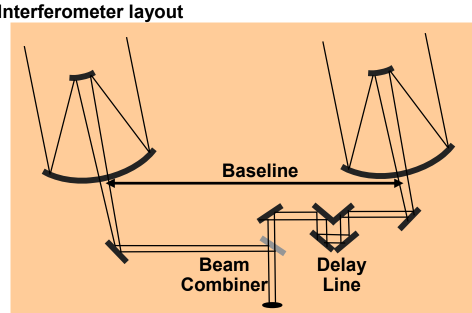
  - Integrated Modeling: Mike Lieber
  - Attitude and Formation Control: Doug Wiemer
- **CU Center for Astrophysics and Space Astronomy (CASA)**
  - MAXIM & X-ray interferometry: Webster Cash, Ann Shipley
- **GSFC Guidance, Navigation and Control Center**
  - Orbit analysis: Landis Markley
  - Formation Flying Testbed: Jesse Leitner
- **JPL**
  - StarLight team

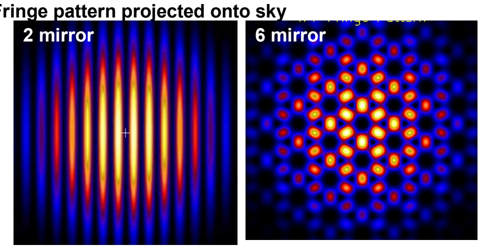
## Stellar Interferometers

- Sampling wavefront with apertures separated by large distance (baseline)
- Angular resolution ∝ 1/baseline
- Well suited for high brightness, high spatial resolution applications
- Destructive interference (nulling) used for blocking starlight in high contrast scenes (star-planet system)
- Rotating, variable-length baseline and multiple wavelengths samples fills u-v plane (spatial freq sampling)
- Synthesis imaging produces image from spatial freq info

Interferometer layout

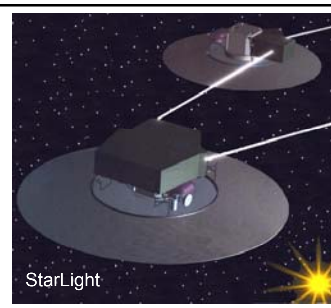


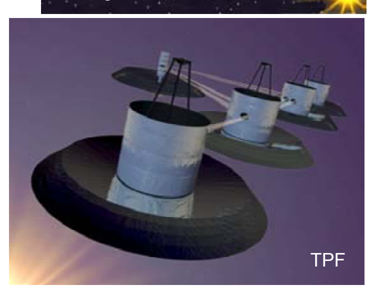

Fringe pattern projected onto sky




## Multi-Spacecraft Interferometers

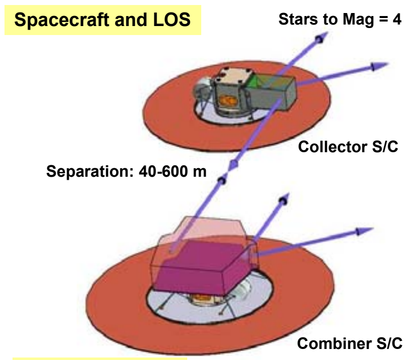
- Advantages
  - Offer weight savings over monolithic structure instruments
  - Easier launch packaging
  - Variable resolution, synthesis imaging produced by adjustable baselines
  - Enabling architecture for some instruments (eg., X-ray interferometry)
- Disadvantages
  - Higher complexity
  - “Lost in space” problem with multiple spacecraft
  - Initialization of formation ("first fringe") is demanding
  - Fault tolerance
  - Mutual contamination

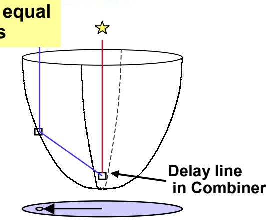


## Current Program: StarLight

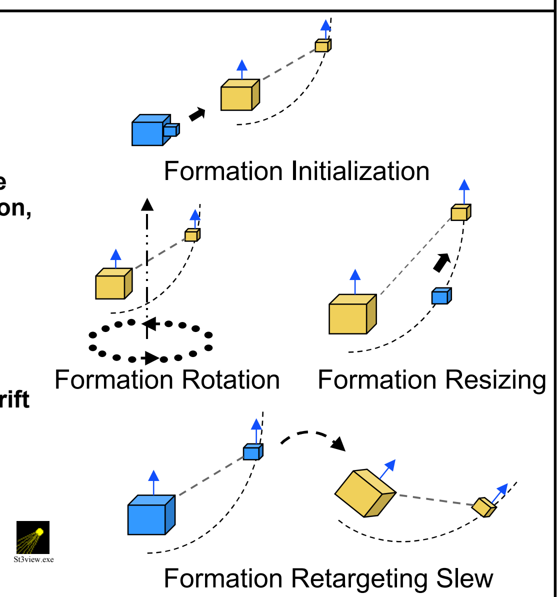
- Launch in 2006 into earth-trailing orbit for 1 year mission
- JPL: Instrument, mission
  Ball: Spacecraft
- Demonstrates high precision formation sensing and control
  - RF system for coarse sensing
    - GPS derivative
    - Resolution: 10 cm range, 2 arcmin angle
  - Laser metrology/siderostat encoder system
    - Out and return for distance; encoders and quad detector for bearing angle
    - Sub-micron distance change, 10 arcsec and 15 milli-arcsec/sec angle change resolution
- Acquires starlight optical fringe
  - Need to locate to within 5 microns of equal path lengths
  - Finding fringe requires relative drift rate measured to < 0.02 mm/sec
  - Tracking of fringe: 4 levels of control of pathlength (S/C + 3-stage optical delay line)




## StarLight Formation Flying

- Need "flat space" to achieve high precision formation flying
- Formation geometry sensors needed to give information on formation, enable closed-loop control
  - RF systems
  - Optical systems
- Precision balanced thrusters and fine attitude control keep drift rates small
- Drift times limited by solar pressure

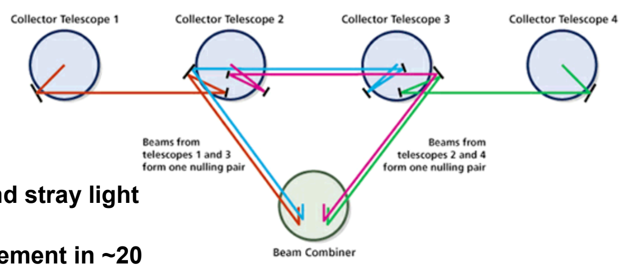


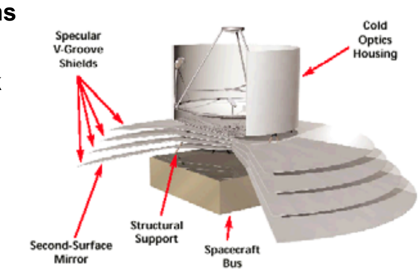
## Potential FF Interferometry Missions

- **Terrestrial Planet Finder**
  - Visible coronagraph or IR interferometer under consideration. Both block starlight to observe direct light from exo-solar earth-like planets
- **Darwin**
  - 6 collector IR interferometer to detect exo-solar planets (similar to IR interferometer version of TPF)
- **Life Finder and Planet Imager**
  - Missions to do higher fidelity spectroscopy (LF) and make images (PI) of earth-like planets around nearby stars. PI uses arrays of TPFs.
- **MAXIM Pathfinder and MAXIM**
  - X-ray interferometers for high spatial resolution imaging of bright X-ray objects
  - Pathfinder is 2 S/C formation; Full MAXIM is ~36 S/C
- **SPECS**
  - Sub-millimeter-wave imager for deep space
- **SI**
  - Stellar imager in the UV-visible
- **LISA**
  - Gravity wave detector with 5 million km baseline using laser interferometry for high precision formation geometry measurements

## TPF Free Flyer Interferometer Configuration

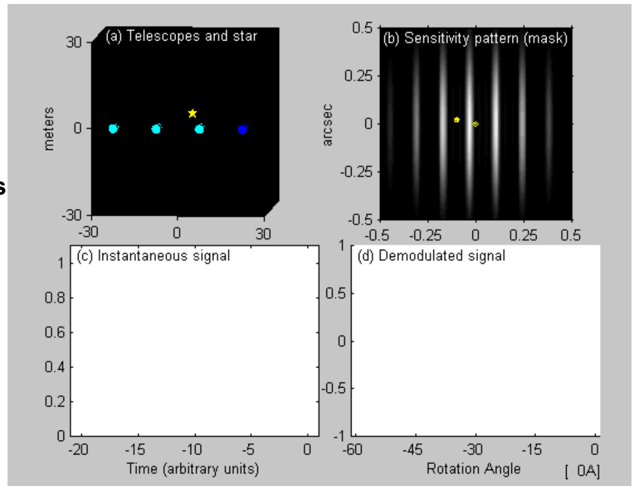
- 2 pairs of nulling interferometers
- Chopping between pairs enhances planet detection
- Beam projection and stray light challenges
- Thermal IR measurement in ~20 spectral bands across 10-20 microns
- Optics passively cooled to ~40K
- Variable baseline to optimally block star image
- Potential long baseline for high resolution astrophysics imaging



## Nulling interferometer planet detection

- Four telescopes used to make two nulling interferometers
- Rotating formation sweeps out planets
- Interferometer outputs combined with alternating relative phase (phase chopping)
- Demodulated signal shows planet, suppresses drifts, symmetric bkgd

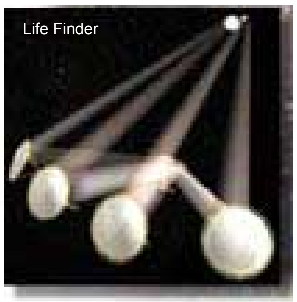


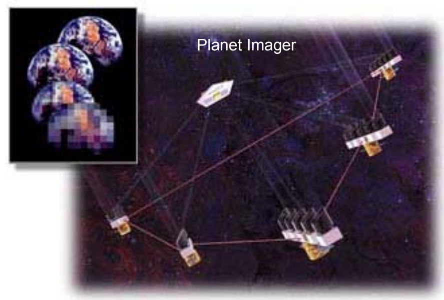

## DARWIN

- Six collector spacecraft and one combiner spacecraft used as a nulling interferometer to block starlight and detect planet emissions
- Operating wavelengths of 5-20 microns
- Baselines of 100 to 200 m
- Angular resolution to 0.01 arcsec
- Also proposed to do high resolution astrophysics imaging
- ESA-funded mission

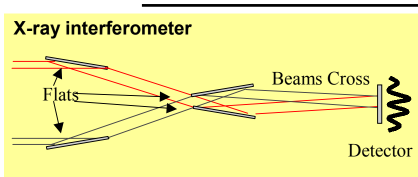
## TPF/DARWIN follow-ons: LF and PI

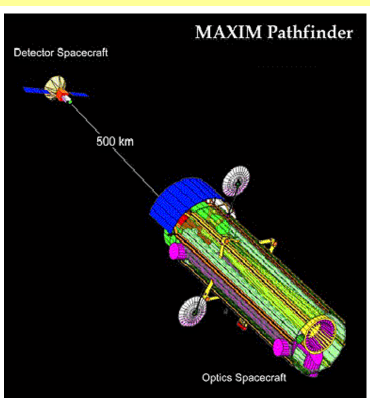
- **Life Finder**
  - Higher spectral resolution measurements of exo-solar planets atmospheric absorption spectra to detect life-related gases
- **Planet Imager**
  - Array of several TPFs (jumbo TPF array)
  - Separation of interferometers up to 6000 km
  - Produces 25 x 25 pixel image of earth-like planet



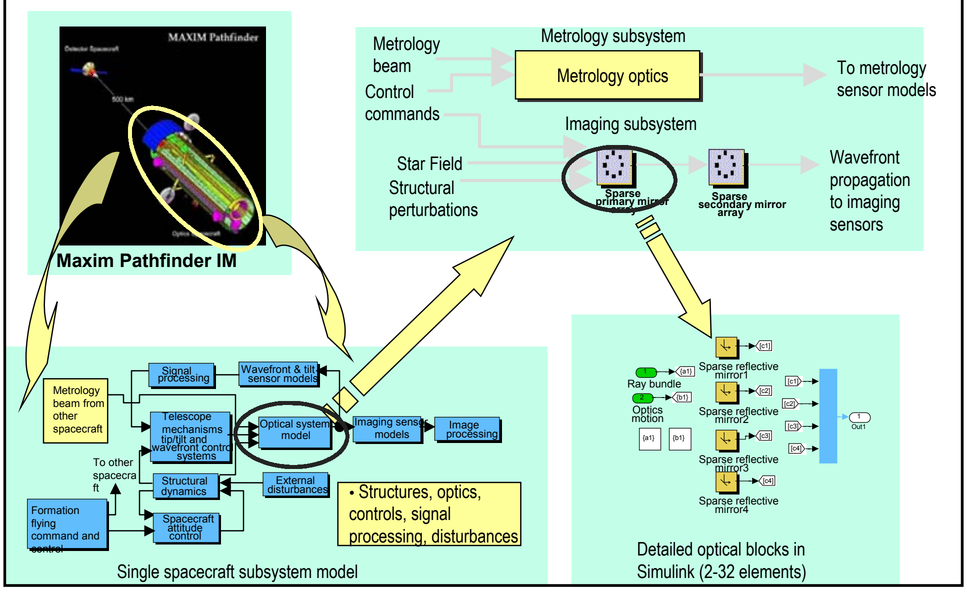

## MAXIM Pathfinder



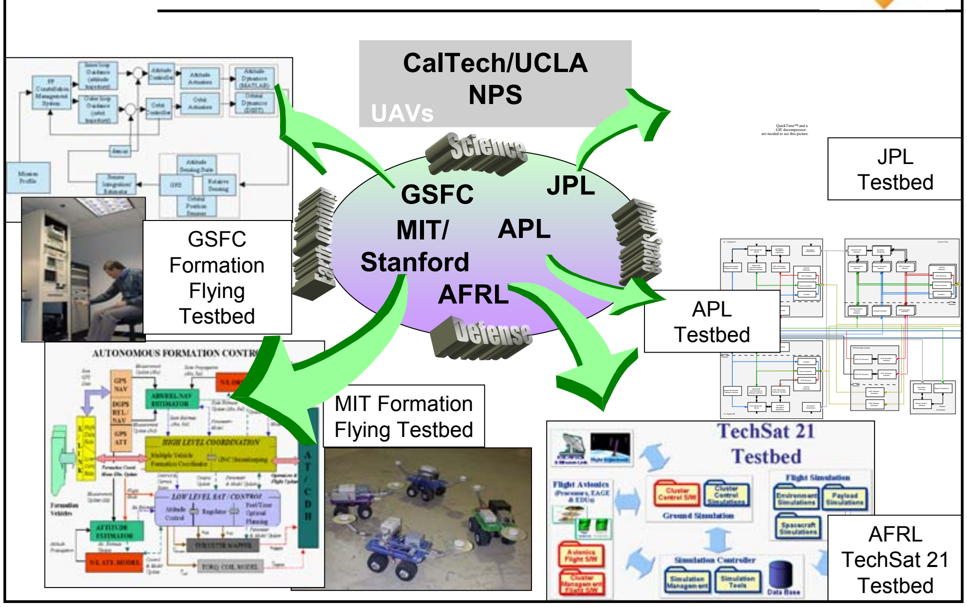




- Interferometer layout uses flats and shallow crossing angle to produce observable fringes
- 16 pairs of interfering mirror pairs produces image at detector
- Demonstrates X-ray interferometry, micro-arcsec image resolution in space
- 1.4 m baseline, 100 $cm^2$ aperture
- Resolution: 100 $\mu$arcsec @ 1 keV photon energies
- Formation requirements:
  - Detector spacecraft lateral stability of $\pm$3 mm
  - Detector lateral pos'n knowledge of $\pm$150 $\mu$m
  - Acquiring and maintaining alignment of object-optics-detector a challenge
- Smaller format detector (25 $\mu$m pixel CCD) could shorten separation to 50 km

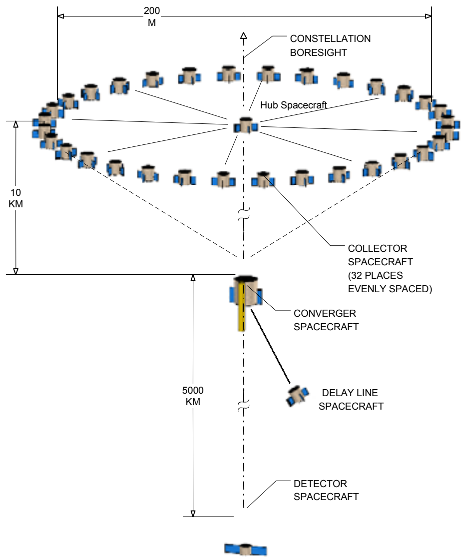
# Integrated Modeling of MAXIM Pathfinder




# Formation Flying Testbeds



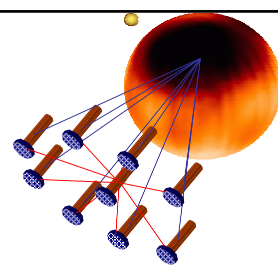
## The Full MAXIM



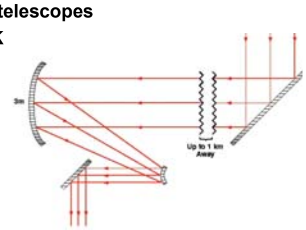

- 0.1 micro-arcsecond resolution at 6keV
- Image event horizons of black holes
- 200 to 1000m baseline
- Maintaining interfering S/C pair spacing very demanding
- Integrated modeling being used to derive system requirements

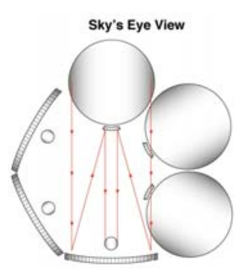

## Other Stellar Interferometers

- **SI: Stellar Imager**
  - Narrowband UV-optical Fizeau interferometer and synthesis imager
  - 10-30 1m aperture telescopes
  - 500 m formation diameter
  - Stellar structure and evolution studies



- **SPECS: Submillimeter Probe of the Evolution of Cosmic Structure**
  - Study sub-mm sky with HST-like resolution and sensitivity
  - Studies of stellar and galactic origin
  - Three 3m aperture telescopes
  - Optics cooled to 4K

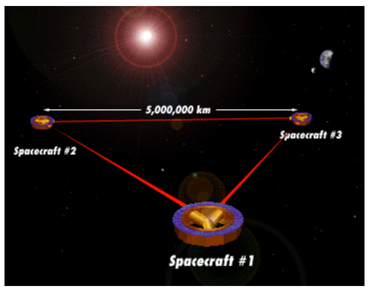




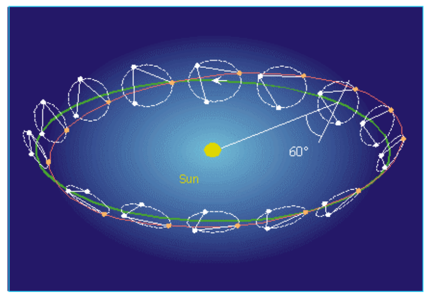
# LISA: Laser Interferometer Space Antenna

- 5 million km separation between spacecraft
- Laser interferometer sensitive to separation changes of 10 picometers
- Measurement of S/C separation changes to give gravity wave detection
- Orbits of 3 S/C give rotating but fixed size formation

Formation geometry




S/C orbits




# Critical Technologies

- Spacecraft:
  - Formation geometry and rate of change sensors
  - Control laws: stability, autonomy
  - Precision attitude and positioning: small, balanced thrusters, quiet wheels
- Instruments
  - Beam projection and wavefront sensing/control
  - Fringe search and tracking, metrology
  - Sources and detectors for metrology
  - Detectors (sensitivity, noise, pitch) for science signals
- General
  - Cryogenics: cryocoolers, passive cooling, cryo actuators
  - Large test chambers
  - High fidelity integrated modeling

# Technology Development Roadmap